Aluminum Success Story

March 2004

The Isothermal Melting Process

Isothermal Melting in Brief:

- Low capital cost
- Simple hardware
- Requires 1/5 the floor space of conventional melting
- No on-site pollution
- Volumetric heating – no thermal stratification
- Homogeneous metal temperature and composition using recirculation
- Reduced dross formation
- Excellent metal quality – low dissolved gas and suspended solids
- 97% net thermal efficiency from electric resistance heat source
- Potential reduction of melt loss from 6% to 2% or less
- Potential annual tacit energy savings of 18 trillion BTU in efficiency gains and an additional 54.5 trillion BTU in melt loss avoidance (including electricity losses)
- Potential carbon emission reductions of 0.6 10^6 MTCE due to increased efficiency and 2.4 10^6 MTCE due to melt loss avoidance
- Crosscutting applications throughout aluminum, copper, glass, steel, iron, platinum, and other industries

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Melting and Heating: Vital to Primary and Secondary Aluminum Production

Effective and efficient application of energy has long been a priority of the aluminum industry. Melting aluminum, holding molten aluminum, and containment during melt processing all carry major opportunities for energy savings because traditional furnaces operate at low efficiencies. Further, these furnaces require expensive materials of construction and often demand frequent repairs.

For the past three years, the U.S. Department of Energy's Industrial Technologies Program has supported the development of a radically new concept for melting aluminum that has demonstrated potential to revolutionize the industry's melting capabilities – the Isothermal Melting Process (ITM). The process can be applied in every segment of the aluminum industry to address the challenge of continuing to meet market demand in the face of the United States' increased reliance on imported primary aluminum ingots and secondary aluminum produced domestically from melted scrap.

Between 1992 and 2002, domestic primary aluminum fell from 48% of the total metal supply to 28%; imported ingots now contribute 30% of the supply (up from 14%) and secondary aluminum consists of 31% (relatively unchanged since 1992). U.S. production of aluminum from scrap outpaced primary aluminum production for the first time in 2001, and 2002 saw this trend continue with 3.2 million tons of secondary production, compared to 3.0 million tons of primary production. The majority of domestically produced primary aluminum is used in molten form and not subject to remelting. As imported ingots continue to displace U.S. prime, the impact of melting on total aluminum energy consumption grows. Clearly, melting is more important to the industry than ever.

Figure 1. The Apogee ITM in Operation

This photo illustrates how the ITM process exemplifies efficient containment of heat. This photo resulted from a combination of natural light and mercury vapor lighting in the lab, and has not been otherwise altered or corrected.

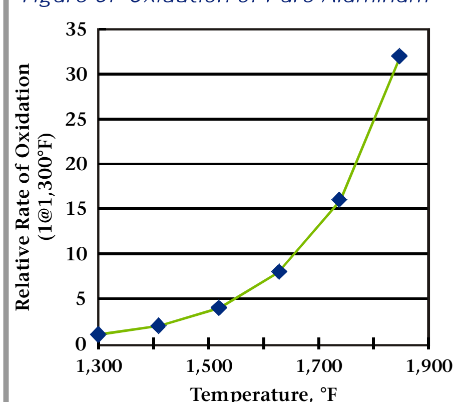
Figure 2. Project Partners

Apogee Technology, Incorporated
Verona, PA

Commonwealth Aluminum
Newport, OH

Drexel University
Philadelphia, PA

Figure 3. Oxidation of Pure Aluminum



Aluminum Industry Roadmap Leads to Improved Melting Technologies

When the Aluminum Association, in cooperation with the U.S. Department of Energy's Industrial Technologies Program (ITP), developed the *Aluminum Industry Technology Roadmap* in 1997, melting emerged as a primary focus for the industry's future. Several R&D priorities called for enhanced melting techniques to reduce dross formation, reuse of a wider range of scrap, and lower melt loss rates.

In 2003, ITP and the Aluminum Association published the revised *Aluminum Industry Technology Roadmap*, reinforcing melting, solidifying, and recycling as strategic imperatives for research and development. The barriers that new melting technologies must overcome included sub-optimal scrap melt rates and low fuel efficiency in melting and holding furnaces.

The Isothermal Melting Process may offer one answer to these challenges. ITM and the Isothermal Melting High-Flux Heaters the process employs directly address the need for advanced melting techniques. This project, a collaboration among ITP, Apogee Technology, Commonwealth Aluminum, and Drexel University (Figure 2), has lead to a promising, revolutionary technology that can dramatically improve energy efficiency in melting and other molten metal processes.

Reverberatory Designs Imprecise, Inefficient

Large open hearth-type reverberatory furnaces are used for melting, holding, and processing during the production of sheet, plate, foil, extrusions, forgings, and engineered castings. These furnaces transfer heat via radiation and operate at efficiencies as low as 15%. Because radiant heat transfer requires large surface areas, significant loss of metal through oxidation occurs at these surfaces. Heat transfer is further hindered by the insulation of surface oxides, leading to high temperature differentials through the depth of the melt.

These fundamental limitations result in exceptionally high melt surface temperatures. A natural gas fired burner has a flame temperature in excess of 3,000˚F. The furnace ceiling and wall surfaces can reach temperatures in excess of 2,600˚F during high-rate firing – over 1,400˚F higher than the typical melt temperature – thus the molten aluminum exceeds the desired withdraw temperature. Because the oxidation rate of aluminum increases geometrically with temperature (Figure 3), an oxide skim layer forms on the metal surface and grows in thickness. The low thermal conductivity and high emissivity of the oxide further reduces burner-to-charge heat transfer, driving surface temperatures in excess 1,700˚F.

Heat transfer away from the metal surface to the remainder of the bath occurs exclusively by conduction in a non-recirculated furnace, as natural convection cannot occur in a top down heating geometry. Temperature stratification within the melt bath increases dramatically with melt rate, and a temperature gradient of over 80˚F per foot of melt depth is not unusual. The burner also requires 19 pounds of combustion air for each pound of gas burned, which may be discharged to the environment at temperatures in excess of 2,000˚F. This inefficient and emissions-intensive process has been compared to heating a cup of coffee with a cigarette lighter.

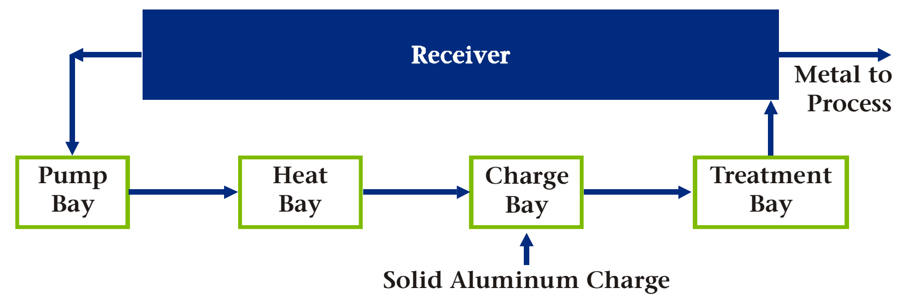
In ITM, heat input is balanced with energy required for melting, permitting thermal homogeneity and essentially isothermal system operation. Additional advantages include: retrofittability, less expensive furnace refractories, reduced damage to refractories and lower frequency of furnace refractory repairs and replacement, reduced energy losses, and improved quality through reduced dissolved hydrogen and entrained oxygen levels.

ITM and the High Flux Heater: Effective, Efficient

Apogee Technology set out to develop and demonstrate a scalable electric melting process for aluminum with a total mass-specific energy input (including containment losses) of less than 750 BTU/lb, 1% melt loss, and without direct in-plant process-generated greenhouse gases. By way of comparison, a typical gas fired furnace requires more than 2,300 BTU/lb energy input for melting, and gross melt loss may range from 2 to 8%, depending on alloy.

Designed as a multi-bay, continuous flow system, ITM employs electronically controlled immersion heaters in a heating bay (Figure 4). A recirculating quantity of molten aluminum within the process provides a heat transfer medium to a continuously fed solid aluminum charge, and metal is withdrawn and returned to the hearth at approximately the same temperature (hence, isothermal melting). High heat flux (130 Watts per square inch or 64,900 BTU per square foot) and external material coatings provide the high-

Figure 4. The Isothermal Melting Process



flux heater with the mechanical and chemical protection that makes this system practical.

Two independent heating sources are used in ITM: one for holding and the other for melting. The first is a patented moderate heat flux (~25 Watts per square inch) system consisting of electric resistance heaters embedded into special thermally conductive refractory panels. This system is known by Apogee as "BSPP," and is independently controlled by cascade logic PID control. The purpose of the BSPP system is to offset holding heat losses, and does not contribute to melting heat requirements.

The second heat source consists of an array of high watt density direct immersion heaters operating at a watt density as high as 140 Watts per square inch. Power is automatically applied to the array heaters as the thermal burden of solid aluminum charge is detected. A second and independent control system modulates array heater input power to offset this thermal burden. The use of waste heat is thus avoided.

The design of the heater array for ITM is critical. Its heat must be intense for high melt rates and spatial efficiency, but must also protect the melt from

Figure 5. An Apogee High Flux Heater

This heater is being used for in-plant testing.

Figure 6. Electric Heater Availability

Parameter	ITM Requirements	Commercially Available
Watt Density	80-130 w/in2	10-15 w/in2
Total Power	50 KW	13 KW
Life	> 4 months	0-6 months
Mechanical	Tough	Fractures

high temperatures that lead to oxidation and melt loss. Heat transfer to the melt and charge occurs by flowing metal around a strategically designed array of submerged heaters. The result is that ITM's electric resistance high-flux heat source has a specific firing rate of over 450,000 BTU per hour per square foot, requires no combustion air, and eliminates emissions. Consequentially, the maximum melt temperature experienced in the ITM process under the most aggressive melting conditions is projected to be less than 90˚F above the desired holding temperature.

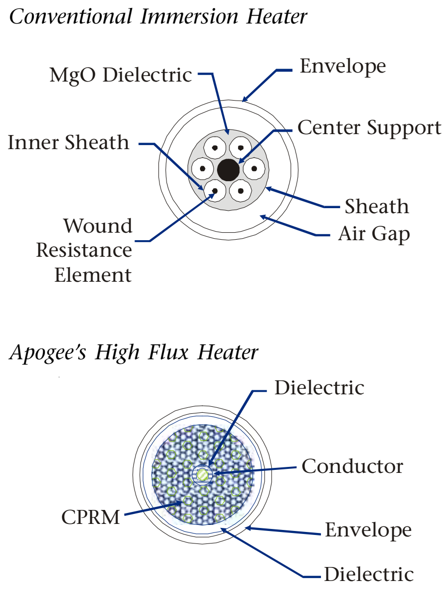
ITM employs newly developed, unique and robust high watt density immersion heaters to transfer heat by conduction into recirculating molten aluminum at demonstrated efficiencies as high as 97%. Melt losses are minimized by eliminating the products of combustion in furnace operation and by replacing the transfer of heat through the surface of the melt with the sub-surface transfer of energy. In addition to the extraordinary energy savings and other benefits to the aluminum industry, the ITM concept and the development of immersion heating elements that were integral to the process are expected to have extensive crosscutting value in other industries.

The High Flux Heater: Resistance for Progress

The high heat flux, direct-immersion resistance heater is the key enabling technology that makes ITM possible (Figure 5). Unlike virtually any other electrical-to-thermal energy conversion process, resistance operates at near 100% thermal efficiency. The limitation to this point has been the commercial availability of a reliable high watt-density, high temperature, and high total power input heater that is also mechanically robust in molten metal (Figure 6). Development of such a heater was critical to ITM's success, and progressed in three phases:

1. A new class of electric resistance materials was created, namely Consolidated Powder Resistive Material (CPRM). Unlike conventional metallic-based resistance materials, CPRM has characteristically high electrical resistivity, a high melting point, and remains flexible at operating temperature. The resistivity of CPRM can be manipulated over a wide range to meet the specific design requirements. Apogee's high flux heater uses a core of this material.
2. A contiguous, multi-component glass based "amalgam" was developed to allow heat transfer to occur at a high heat flux and mini-

Figure 7. A Paradigm Shift in Heater Design Approach



mum temperature gradient. Commercially available heaters usually use packed magnesium oxide particulate as a heat transfer/dielectric material that is relatively inefficient in transferring heat. By contrast, the glass amalgam flows into a heater and later solidifies as a continuous solid. The bulk thermal conductivity is higher than packed magnesium oxide by a factor of 100.

3. A thermally conductive and mechanically robust protection sheath was required to protect the heater from reaction with highly aggressive molten aluminum. The development of this sheath was the most challenging aspect of the ITM program due to the rigorous thermal, mechanical, and chemical demands of the environment.

Many of ITM's benefits are directly derived from the immersion heater design (Figure 7). Electric resistance through conductive heat transfer from immersion heaters allows for thermal efficiencies as high as 97 percent, eliminates on-site pollution, and avoids detrimental combustion gas contact with aluminum is avoided. The newly developed materials give the immersion heaters a highly conductive, impact-resistant ceramic coating on a metallic sheath, combined with a highly thermally conductive, dielectric integral-coupling medium between the sheath and the heat- producing element. CPRM used as a heat-producing element allows the heater to reliably operate at much higher temperatures and total power input than immersion resistance heaters that are commercially available today.

The ITM process achieves many of the goals outlined in the aluminum industry roadmaps, including:

- operates at well under half of the energy consumption required for conventional melting
- decreased melt loss (1% vs. 6%)
- reduced dross generation
- produces no in-plant emissions
- practical for large-scale aluminum operations
- future versions can be used in retrofit applications for existing furnaces
- derivative heaters can be applied to energy-efficient heating and holding applications
- requires less than 25% of the floor space as compared to conventional melting

Varied Applications, Crosscutting Benefits

Potential energy savings offered by this technology extend throughout the aluminum field and to sectors in many other industries. Within the aluminum industry, benefits can be realized in applications such as: immersion

ITM and the Turboelectric Ladle (TeL)

An ITM based aluminum melting "hub" is being developed to distribute high-quality molten metal for small- to moderate-sized castings production facilities. Molten metal delivery is accomplished using another innovation made by Apogee Technology in collaboration with Wabash Alloys, known as the Turboelectric Ladle (TeL). Essentially an electrically self-heated vessel containing up to 30,000 pounds of aluminum, the TeL's integral heating system allows metal to be heated and maintained by electric resistance heaters at a temperature near the metal dispensation temperature, providing approximately 95% thermal efficiency (Figure 8).

Delivery occurs over the road with virtually no distance restriction because metal is maintained at temperature. Once at the customer's location, a TeL can be powered by in-plant electricity and used to dispense on-grade metal over any period of time.

Figure 8. 30,000 pound Turboelectric Ladle Developed with Wabash Alloys

ITM offers energy savings to address a changing metal supply

As domestic primary production of aluminum has sharply decreased, the industry has increasingly turned to secondary markets and imported primary aluminum.

Essentially all secondary metal must be remelted; in addition, all imported primary aluminum must be remelted, therefore, the "remelt pool" is quite large (and growing): 25 billion lbs/year is a tenable number.

ITM stands as an effective and efficient means to address this growing portion of the overall metal supply. Analysis from a November 2003 melt loss experiment with the 300 lb/hr ITM demonstrated 0.40% net melt loss, with an uncertainty of +/- 0.21% (typical melt loss is 4-8%).

Other benefits include:

Increase in overall thermal efficiency

- Reduction of specific melting energy from 2,100 to 550 BTU/lb
- Total potential tacit energy savings per year: $18x10^{12}$ BTU

Melt loss avoidance

- Net melt loss reduced from 5% to 1%
- Potential to save 1 billion pounds @ 14 kWh/kg Al
- Total potential tacit energy savings (including losses) per year: $54.3x10^{12}$ BTU

Annual savings (@ $\$5/10^6$ BTU) is $360 million

heating (i.e. caster holding furnaces); retro-fit, drop-in heater/circulator for existing melting furnaces; resistance heated troughs; and just-in-time melting/flexible ingot manufacturing. Other metal industry sectors can also benefit, such as copper melting and treatment (degassing), magnesium, steel, precious metals (particularly platinum), riser heat supplementation for larger castings, and other applications to 2,800°F.

A portable (trailer-based) ITM system is being planned for the on-site melting of aluminum scrap. Such a system could offer clean and efficient melting at scrap collection sites and landfills throughout the country, while avoiding unnecessary transportation costs and cross contamination of alloys.

Not limited to metal melting, the benefits of ITM can also be realized in a variety of heating applications, such as flexible heaters, radiant heaters, as a low-cost alternative to wound elements, and in high-response heaters. With some modifications to the heater envelope, materials industries can apply ITM in the manufacturing of borosilicate and other glasses.

Continued Progress, Anticipating the Future

Apogee's collaboration with ITP has generated notable success, and several of the goals outlined in the initial plan have been achieved:

- Demonstration and operation of an immersion heater at a watt density of 130 Watts per square inch over a continuous six month period in molten aluminum (December, 2002).
- Industry introduction of the high watt-density immersion heater elements (March, 2003).
- Optimization of the heater's internal design to provide a total input power of 50 kW.
- Completion of the design, construction, and operation of a 300 lb/hr (300 lb/hr @ 487 net /666 gross BTU/lb) heating chamber (December, 2003).
- Development of a mathematical model to demonstrate temperature excursion expectations and provide scale-up to a 10,000 lb/hr melt rate.
- The design of a 5,000 lb/hr ITM melter (February, 2004).

Now that the 300-pound/hr system is fully operational, attention will focus on:

- Demonstration of long-term heater performance.
- Construction of the 5,000 lb/hr ITM melter at Commonwealth Aluminum-Newport (completed by December, 2004).

Future steps will include:

- Development projects that build on Apogee's experience and capabilities to optimize ITM containment systems.
- The development of an ITM retrofit system for existing furnaces.
- Development of an on-site/off-line ITM with a detainable, TeL-based delivery system in partnership with an automaker.
- Demonstration of advanced melting and handling techniques that could save one plant an estimated of $20-30M/year (based on customer's calculations).

- Design and construction of a complete 10,000 lb/hr ITM system with related sensor and control methodology and melt chamber.
- Further investigation of applications in copper, magnesium, platinum, and other targeted industries.
- Scale-up to a 75,000 lb/hr system.

The Future of Industry: Enabling New Technologies

As new melting technologies continue to emerge, the aluminum industry and our nation will increasingly enjoy the inherent benefits of recycled aluminum. Primary aluminum production will benefit through the implementation of advanced heating methods, and cross-cutting applications will extend energy savings benefits beyond aluminum with significant collateral environmental impact.

Projects such as Apogee's ITM and High Flux Heater are good examples of the type of advanced technologies that the DOE's Industrial Technologies Program seeks to support. These technologies are revolutionary in nature, technically tenable, and represent a paradigm shift in energy conversion used to heat and melt materials; but, they can be risky. The success of an inherently complex development process often calls for resources transcending those of a single company.

Acting as a bridge between idea and implementation, ITP serves to minimize this risk by facilitating collaboration within the industry, and encouraging interaction with national laboratories and universities. By continuing to work with the aluminum industry and its technology providers, ITP nurtures an environment of innovation while delivering maximum energy savings to the nation.

Figure 9. The Apogee ITM Team

The Apogee ITM team the night of its first successful operation.

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A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

U.S. Department of Energy
Energy Efficiency and Renewable Energy

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Technical Accomplishments

High Heat Flux Direct Immersion Heater

- High flux (80 to 130 w/in^2)[1]
- Fracture tough thin metallic composite sheath (MOR>10,000psi)[2]
- BI @ h = 2,000 BTU/ft^2-hr-°F = 1.7 (conventional heater BI > 7)[3]
- Greater than 6 month life-span
- Uses wound wire or Apogee CPRM heating elements
- CPRM is capable of 50 kWh/heater and temperatures greater 2,000°F

Adaptation of Baffle and Side Pocket (BSPP) Heating to ITM Application

- 20 w/in^2 immersion heating
- 166 BTU/lb holding overhead for 300 lb/hr ITM
- Can be geometrically configured

Successful Start-Up of 300 lb/hr ITM Prototype

- Demonstrated net specific melting energy (SME): 487 BTU/lb
- Demonstrated gross SME: 666 BTU/lb
- Demonstrated net melt loss: None detected (using heavy charge)[4]
- Demonstrated specific melt rate: 432,091 BTU/hr-ft^2
- Expandable within footprint to greater than 500 lb/hr

Other Accomplishments

- Development of plasma spraying practices leading to consistent and reproducible results
- Development of compliant, fracture tough YSZ[5] coating
- Development of vapor-phase magnesium intrusion/preoxidation YSZ sealant
- Refinement of purity and particle size distribution of CPRM
- Demonstration of externally consolidated CPRM pellets

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1 *Typical watt density range for traditional electrical resistance heating of molten aluminum is 10-15 w/in^2*
2 *MOR = modulus of rupture*
3 *BI = Biot number, the ratio of heat transfer coefficient to thermal conductivity multiplied by a characteristic dimension. In this case, lower is better.*
4 *Recent tests measured 0.4% net melt loss for 300 lb/hr ITM, industry norm is about 2-8%.*
5 *YSZ = yttria stabilized zirconia*

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